GOATS 2011
Adaptive and Collaborative Exploitation of 3-Dimensional Environmental Acoustics in Distributed Undersea Networks

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LONG-TERM GOALS

To develop net-centric, autonomous underwater vehicle sensing concepts for littoral MCM and ASW, exploiting collaborative and environmentally adaptive, bi- and multi-static, passive and active sonar configurations for concurrent detection, classification and localization of subsea and bottom objects..

OBJECTIVES

The MIT Laboratory for Autonomous Marine Sensing Systems (LAMSS) has continued its interdisciplinary research under the GOATS project, initiated in 1998 in collaboration between MIT and NURC, and as such a seamless continuation of the research effort under the previous grant N00014-08-1-0013. The principal objective is to develop, implement and demonstrate real-time, onboard *integrated acoustic sensing, signal processing and platform control* algorithms for adaptive, collaborative, multiplatform REA, MCM, and ASW in unknown and unmapped littoral environments with uncertain navigation and communication infrastructure.

A related objective is the development of a nested, distributed command and control architecture that enables individual network nodes of clusters of nodes to complete the mission objectives, including target detection, classification, localization and tracking (DCLT), fully autonomously with no or limited communication with the network operators. The need for such a nested, autonomous communication, command and control architecture has become clear from the series of experiments carried out in the past under GOATS and several experiments carried out under the UPS PLUSNet program.

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APPROACH

The GOATS (Generic Ocean Array Technology Sonar) research program is a highly interdisciplinary effort, involving experiments, theory and model development in advanced oceanography, acoustics, signal processing, and robotics. The center-piece of the research effort has been a series of Joint Research Projects (JRP) with the NATO Undersea Research Centre (NURC). The joint effort was initiated with the GOATS' 98 pilot experiment followed by a series of annual field experiments, most recently the GLINT'08, '09, and '10 experiments focusing on adaptive autonomy for multid\static active surveillance networks. In addition to the field experiments involving significant resources provided by NURC, GOATS uses modeling and simulation to explore the potential of autonomous underwater vehicle networks as platforms for new adaptive sonar concepts for undersea networks.

The fundamental approach of GOATS is the development of the concept of a network of AUVs as an array of *Virtual Sensors*, based on fully *integrated sensing, modeling and control*, reducing the inter-platform communication requirements to be consistent with the reality of shallow water acoustic communication in regard to low bit-rate, latency and intermittency

In regards to applications to MCM, GOATS explores the use of bi-static and multi-static Synthetic Aperture created by the network, in combination with low frequency (1-10 kHz) wide-beam insonification to provide coverage, bottom penetration and location resolution for concurrent detection, localization and classification of proud and buried targets in SW and VSW. The signal processing effort is therefore centered around generalizing SAS processing to bi-static and multi-static configurations, including bi-static generalizations of auto-focusing and track-before-detect (TBD) algorithms. Another issue concerns the stability and coherence of surface and seabed multiples and their potential use in advanced low-frequency SAS concepts.

More recently, the GOATS effort has transitioned towards the development of similar, autonomous network concepts for passive littoral surveillance, e.g. the Undersea Persistent Surveillance (UPS) program, initiated in 2005 and completed in 2008. PI Schmidt was lead PI and Chief Scientist for the UPS PLUSNet Program, which developed a network concept of operations based on clusters of AUV and gliders, connected via acoustic communication, and intermittent RF communication with the operators through periodically surfacing gliders. A prototype network concept with a hybrid, cooperating suite of underwater and surface assets was successfully demonstrated in PN07 in Dabob Bay, WA. As in the past GOATS effort, the MIT marine autonomy effort is utilizing the open-source MOOS control mission control software originally developed and funded under GOATS, in combination with the IvP multi-objective optimization helm, developed at NUWC and MIT. To take advantage of the robustness of the native control software, while at the same time retaining the flexibility in regard to sensor-driven adaptation and collaboration, MIT LAMSS has developed a new nested control architecture, where the lower level control of the nodes, as well as the overall field control can be performed using arbitrary third-party software, while the medium level, adaptive and collaborative control of the nodes and the clusters is performed within the MOOS-IvP software framework.

Such a nested command and control infrastructure with heterogeneous assets invariably need translation to and from a common communications protocol. Starting with the MB'06 experiment, MIT and Bluefin AUVs were controlled using a new, so-called "back-seat driver" paradigm wherein low-level commands to the Bluefin control software were translated and conveyed by a specially designed MOOS module.

The mid-level, adaptive and collaborative control of the network nodes is carried out using MOOS in combination with the new multi-objective, behavior-based IvP control framework developed within MOOS by Michael Benjamin at NUWC/MIT. The core of this architecture consists of a behavior-based control system which uses multiple objective functions to determine the appropriate course, speed, and depth of the platform at every control cycle (typically 10-20 Hz). The desired course of action is determined by computing a multi-function optimization over the objective functions using the Interval Programming Model developed by Benjamin which provides a very fast optimization suitable for small vehicles.

The development of GOATS concepts is based heavily on simulation, incorporating and integrating high-fidelity acoustic modeling, platform dynamics and network communication and control. In regard to the environmental acoustic modeling, MIT continues to develop the OASES-3d modeling framework for target scattering and reverberation in shallow ocean waveguides. As was previously the case for the MCM effort, the approach has been to develop a complete system simulation capability, where complex adaptive and collaborative sensing missions can be simulated using state-of-the-art, high-fidelity acoustic models for generating synthetic sensor signals in real time. This is being achieved by linking the real-time MOOS simulator with a generic, high-fidelity acoustic simulation framework GRAM, which in 'real-time' generates element-level timeseries using Green's functions using legacy environmental acoustic models such as OASES, KRAKEN and BELLHOP.

WORK COMPLETED

Classification of Underwater Targets by AUV Sampled Bistatic Acoustic Scattered Fields

The goal of this research is to investigate the combination of signal processing, machine learning and AUV behaviors for the onboard classification of underwater targets. The final goal of this project is to have a vehicle loaded with appropriate models able to do onboard classification fully autonomously using only scattered field data collected as passes through the bistatic scattered field of different target types. The simulation work done so far has been mostly on the classification of spherical verses cylindrical targets in the presence of rough bottom scattering.

The process to achieve target classification consists of two key parts: model training/analysis and target classification. The model training/analysis aspects can be carried out offline, while target classification must be carried out in real time on the vehicle. In the last year, appropriate processing chains have been written for both steps in target classification, and have been demonstrated with the LAMSS MOOS-IvP simulation environment. The development of these processes is in preparation for the GOATS'14 experiment, planned for January 2014.

The training and analysis steps for the formulation of machine learning models have been finalized using the groundwork laid in previous years. The training process takes in a full field scattered field and generates training and testing example sets using that data. A Support Vector Machine (SVM) is then used to train a model for classifying new target data. Analysis of independent test sets are used to derive a confidence model and critical regions for the AUV to sample. The full field scattered field may be simulated using the SCATT-OASES acoustic package or may be derived from a real field collected by an AUV. In the latter case, the data is input either as a log file containing vehicle position and target amplitude output by onboard signal processing, or as a directory where acoustic binary files may be found.

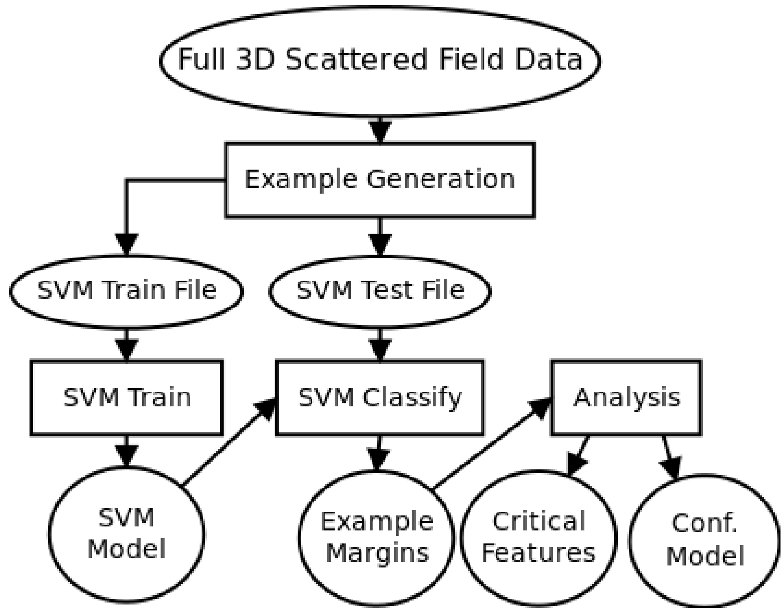

Figure 1. Flow chart of the Training/Analysis Program.

In addition to the training process, a classification processing chain has been written this year to calculate target classification and confidence while guiding the vehicle to regions of the scattered field that give a high probability of correct classification. A vehicle loaded with the results from the training/analysis process is then able to classify underwater targets using a combination of vehicle behaviors, signal processing and machine learning classification. Once a target track is sufficiently confident, the target classification behavior and processing chain are initialized. The target classification behavior provides the vehicle with a path to follow that improves the likelihood of confidence target classification. While it follows this path, the classification processing chain calculates target amplitude and periodically classifies the list of received target amplitudes, calculating confidence. This process continues until a confidence threshold is reached or the vehicle path is completed. Testing has been carried out using the LAMSS MOOS-IvP simulation environment, using scattering amplitudes derived from acoustic simulations.

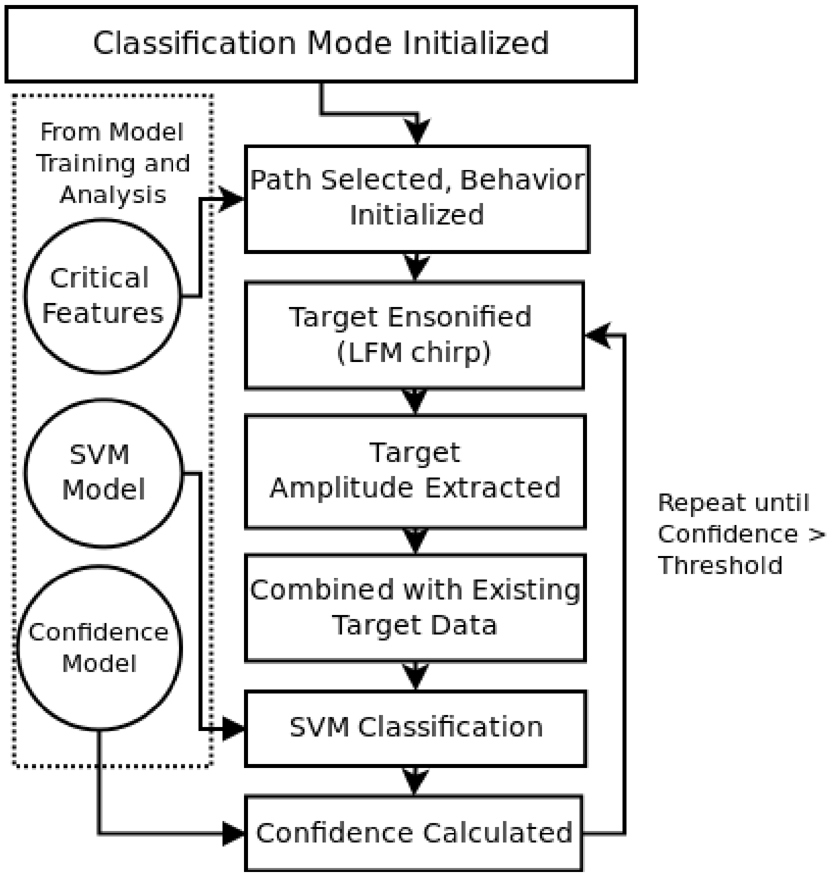

Figure 2. Classification Processing Chain.

Vehicle behaviors have been developed for use in collecting full data sets from real scattered acoustic fields and for guiding the vehicle through the parts of the scattered field of greatest interest for classification. The full data sets collected using the full field sample behavior are then used in the model training/analysis steps. In this behavior, the vehicle remains broadside to the target except in a region in the forward scatter direction where the arrival times are too close together for meaningful data to be extracted. In the transition region, the vehicle moves between radii.

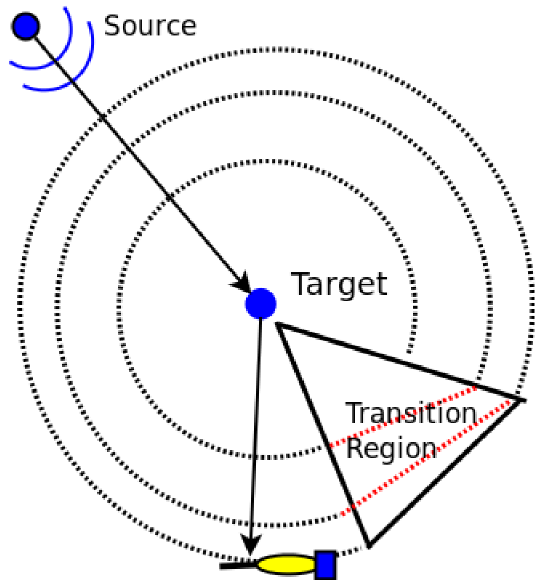

Figure 3. The full field sample behavior.

In the classification mode behavior, the vehicle hits a set of empirically derived critical waypoints while staying as broadside to the target as possible. An A* search using a weighted cost function of "broadsideness" and path length is used to calculate the optimal path through the field subject to vehicle turn radius and pitch angle constraints. Additional nodes are generated if necessary to improve broadside behavior.

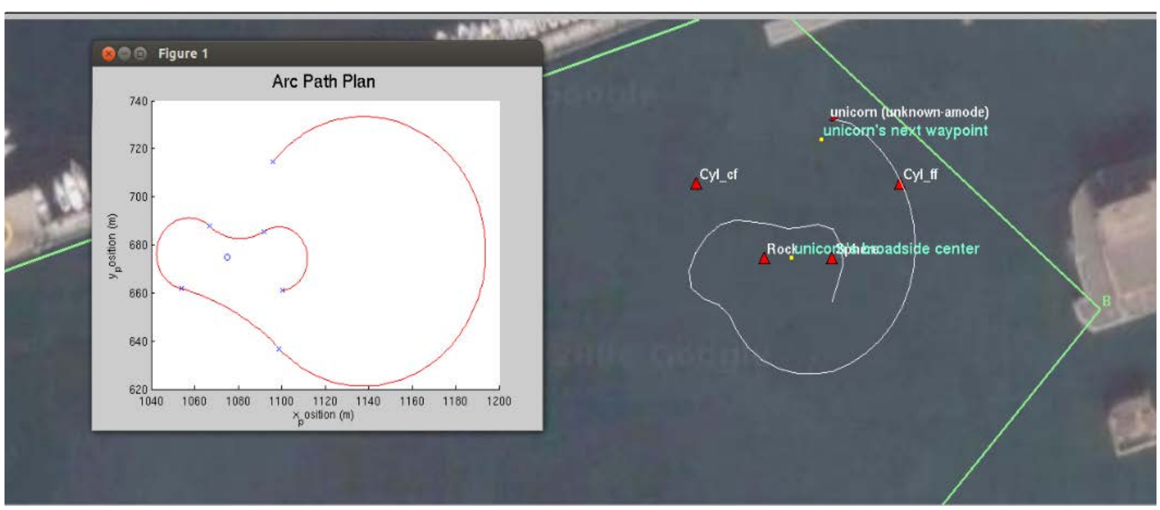

Figure 4. Vehicle in LAMSS MOOS-IvP simulator running a critical waypoint sampling behavior, compared with desired path.

Additional preparation for the GOATS'14 experiment has involved readying the payload and array. Of upmost concern for a bistatic acoustic experiment is time synchronization: because source and reciever are not co-located, and the AUV is submerged, exact time sychronization to less than 10us is essential. This is achieved through the use of a Symmetricom SA.45s Chip Scale Atomic Clock (CSAC). The CSAC provides an onboard time source with better than nanosecond accuracy, and is synchronized to a GPS clock on the surface. With the source pulse-per-second (PPS) synchronized to the GPS signal and the computer clock and A to D converters PPS synchronized to the CSAC, this setup ensures that the start of the second is a known quantity. This care in time synchronized should produce a superior acoustic bistatic data set. The inexpensive CSAC technology also makes a bistatic acoustic approach more feasible.

Autonomous Adaptive Oceanographic Feature Detection and Tracking with AUVs

In testing AUV autonomy algorithms and behaviors, it is essential to have a robust AUV simulation environment to mimic real-world conditions. To this end, MSEAS 4D dynamic ocean models have been integrated into the LAMSS AUV autonomy simulation environment for research and behavior development purposes. This was accomplished using a new Octave-MOOS interface, *pOctaverMIT*, based on the original *pOctaver* code from a group at CMRE in La Spezia, Italy. With the integrated MSEAS models, we were able to demonstrate end-to-end simulations of AUVs & gliders operating in realistic dynamic ocean environments, collecting environmental data (i.e., temperature, salinity, flow velocities) from simulated sensors, much as real vehicles would in an actual ocean environment. The primary use thus far for the MSEAS models as a simulation environment have been for testing oceanic front boundary tracking behaviors that have been developed over the past year for use on board AUVs.

Off the east coast of the United States flows the Gulf Stream, which is a large stream of warm water flowing south to north just off the continental shelf. The interface of the Gulf Stream with the continental shelf water in the Mid-Atlantic Bight region creates a strong oceanic front along the shelf break, which is of much interest to scientists. To study dynamic ocean features on spatial scales as large as this front, it may be more efficient to use AUVs equipped with an autonomous and environmentally-adaptive front tracking behavior, rather than by pre-planning a non-adaptive AUV front tracking mission that would require monitoring and updating remotely by a human operator. To test this theory, an autonomous and adaptive front tracking behavior, *BHV_FrontTrack*, has been developed for individual AUVs (though it can easily be deployed on many AUVs at once) and is currently being tested and polished using MSEAS models in AUV simulations.

2D (horizontal space) front tracking algorithms have been verified in a static ocean model, and are currently being tested & evaluated in simulation using an MSEAS dynamic ocean model of the Mid-Atlantic Bight as the simulation environment. The concept of 2D front tracking is shown in Fig. 5. The challenge to front tracking with AUVs lies in the disparity between the characteristic spatiotemporal scales of the dynamic ocean environment and the spatiotemporal coverage and resolution achievable by a single (or multiple) AUV(s) in that environment. This is where collaborative multi-AUV missions become important.

3D front tracking concepts are currently being developed for implementation as MOOS-IvP behavior algorithms. These include a horizontal helix behavior (see Fig. 6) that can be performed by one or more AUVs, where the central axis of the helix lies along the approximate front boundary at a given depth. Both the helix and a simpler zig-zag front tracking behaviors can be extended to cover an even greater depth range by distributing multiple AUVs across a range of depths and at roughly the same position in the horizontal to perform front tracking in a coordinated manner while improving the synopticity of the data set collected, as illustrated in Fig. 6. These collaborative AUV behaviors are currently being developed and tested such that multiple AUVs can autonomously coordinate their front tracking behaviors and distribute themselves along a front boundary (in the horizontal and vertical planes) to improve spatiotemporal coverage and resolution in the collected data set.

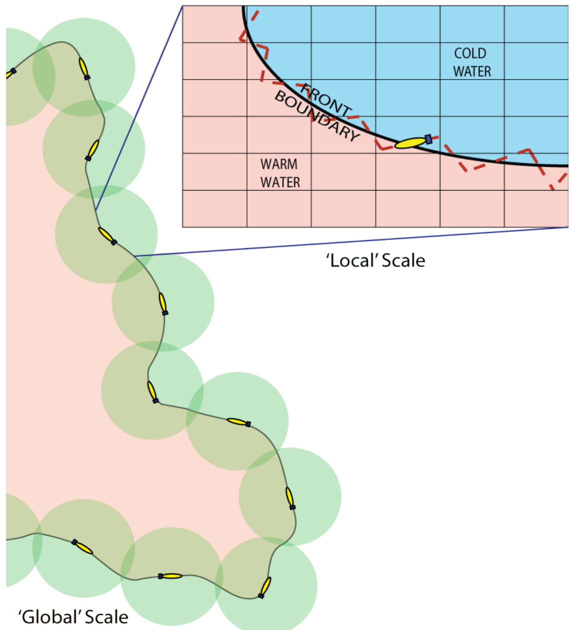

Figure 5. Concept for multi-AUV coordination and tracking of a front boundary on the 'global' scale, and 'local' scale tracking of the front boundary using a zig-zag pattern across the boundary in the horizontal plane. The circles are range rings around each AUV, specifying the range within which all samples collected by the AUV may be considered current measurements of the front (all samples within the characteristic time and spatial scales of the dynamic front).

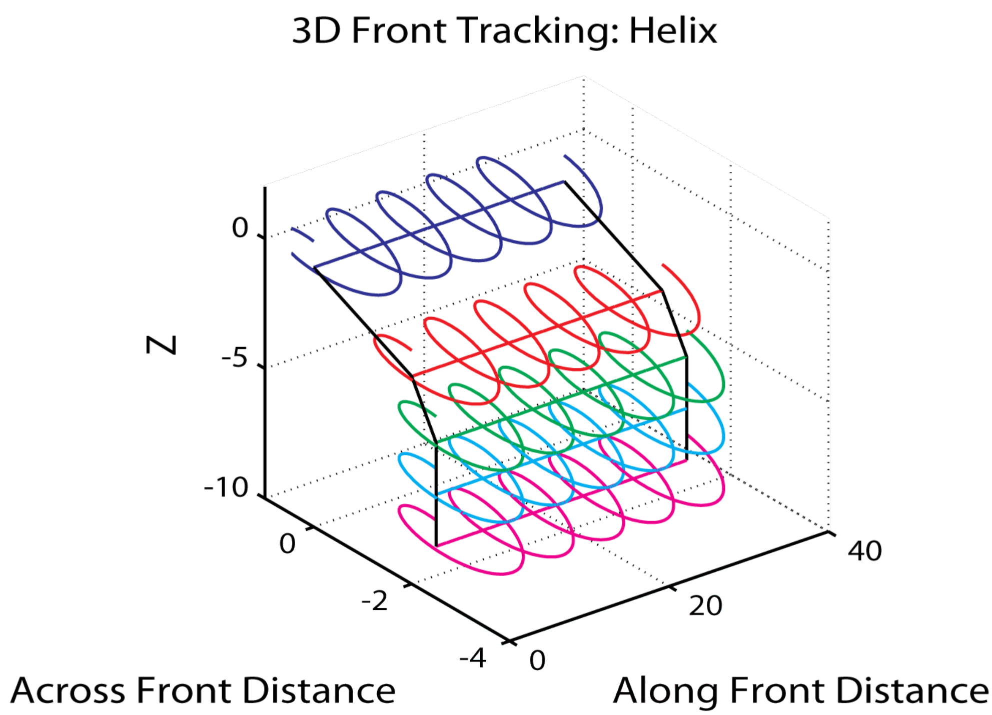

Figure 6. Concept for multi-AUV coordination and tracking of a 3D front boundary using a horizontal helix behavior. Each helix represents the path that a single AUV would take, where the central axis lies along the locally estimated front boundary. The AUVs are separated in depth and somewhat coordinated in horizontal motion to provide a 3D data set with even more depth coverage than a single AUV helix. The 3D position of the front is delineated by the black vertical curve.

Matched-Beam Differencing: Depth-tracking of a near surface target from the deep ocean
In the past year, a depth-tracking algorithm has been developed to determine the depth, in real time, of a near surface source from a vertical line array in the deep ocean. The algorithm, known as Matched-Beam Differencing (MBD), takes advantage of the Lloyd mirror interference patterns that the near surface targets create.

As the target moves in range, the major features of interest (nulls from Lloyd mirror pattern) from the beamformer output are extracted as in Figure 7. This new signal is cross-correlated with an entire dictionary of known signals for varying source depths in order to determine the actual target depth. The number of nulls is highly dependent of frequency and source depth. This method can be used with single frequency or broadband sources. In the broadband case, multiple frequencies can be used in order to get a better estimate of depth and range.

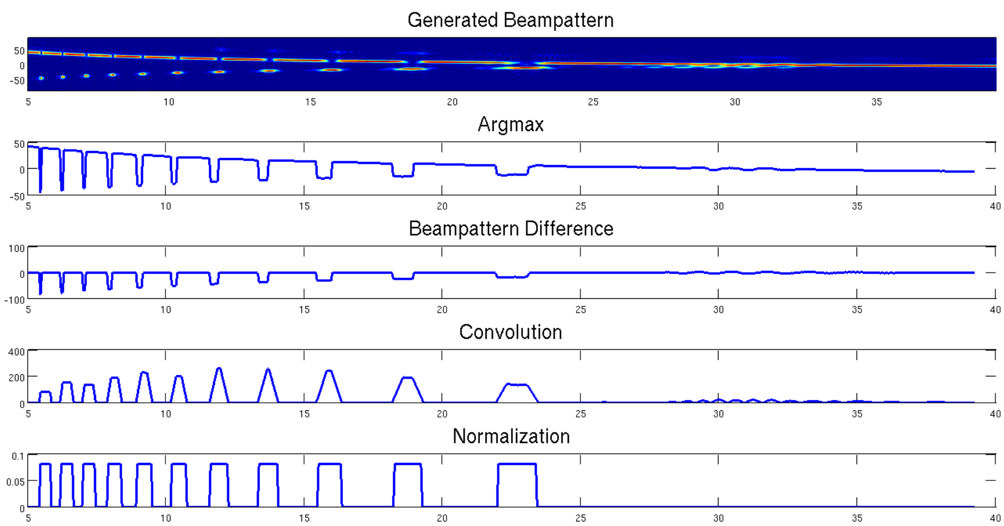

Figure 7: Making the Matched-beam difference signal. From top down: a). Beampattern vs. Range of 100m depth 150Hz source, b). Find Maximas, c). Take differencae with no-null beampattern, d). Convolve with boxcar e). Normalize

Autonomous Network Communication and Control
Goby: Practical acoustic networking
In 2013, we completed the first release of the second version of the Goby Underwater Autonomy Project (Goby2), which provides a field tested suite of tools for underwater and other "slow link" communications situations. The Goby2 generic modem driver was used to include direct support for Iridium satellites and the SonarDyne Avtrak acoustic modem. Additional work and at-sea testing was completed on the very low overhead vehicle position telemetry system presented in [4], which is discussed in the results section.

iFrontSeat: A unified approach to deploying autonomy on a diverse collection of vehicles
For the broad applicability of our autonomy systems, we create a separation between the "frontseat" computer (provided by the vehicle manufacturer and is typically proprietary) and the "backseat", which runs the high level autonomy (typically the IvP Helm), sensing, and communications (typically Goby) components.

Not surprisingly, a piece of software is required to interface between the "frontseat" and the "backseat". Historically, a new interface has been written for each vehicle, which led to poor scalability and low quality in certain interfaces. We developed the new application iFrontSeat (Schneider, iFrontSeat: a new approach for writing extensible MOOS-IvP "frontseat"-"backseat" payload interface drivers, 2013) which aims to address these problems by providing a single open source implementation of the connection to the "backseat" while providing a structured well-defined extensible interface for writing different "frontseat" drivers. Currently, a driver has been developed and tested for the Bluefin Robotics family of AUVs.

RESULTS

Classification of Underwater Targets by AUV Sampled Bistatic Acoustic Scattered Fields

A number of simulation experiments have been carried out to demonstrate the feasibility of a machine learning approach to classifying spherical verses cylindrical underwater targets using only bistatic scattered field amplitudes. A set of experiments were set up using the SCATT-OASES acoustic package, to show performance in different frequencies and target positions, as well as to demonstrate robustness to navigation error. The environment is assumed to be an 8m deep harbor with a fluid sand bottom (modeled using an isotropic Goff-Jordan power spectrum), with a source located at 3m depth and 50m from the target, approximately the same as will be encountered in the GOATS'14 experiment. An SVM model is trained using a dataset containing about 2000 training examples, each consisting of amplitude samples of between 5 and 20 waypoints through the scattered field. An independent 1000 example training set is used to assess the models. As a base case, a 'clean' model was trained, and tested using a test set without any shifts, environmental changes or errors.

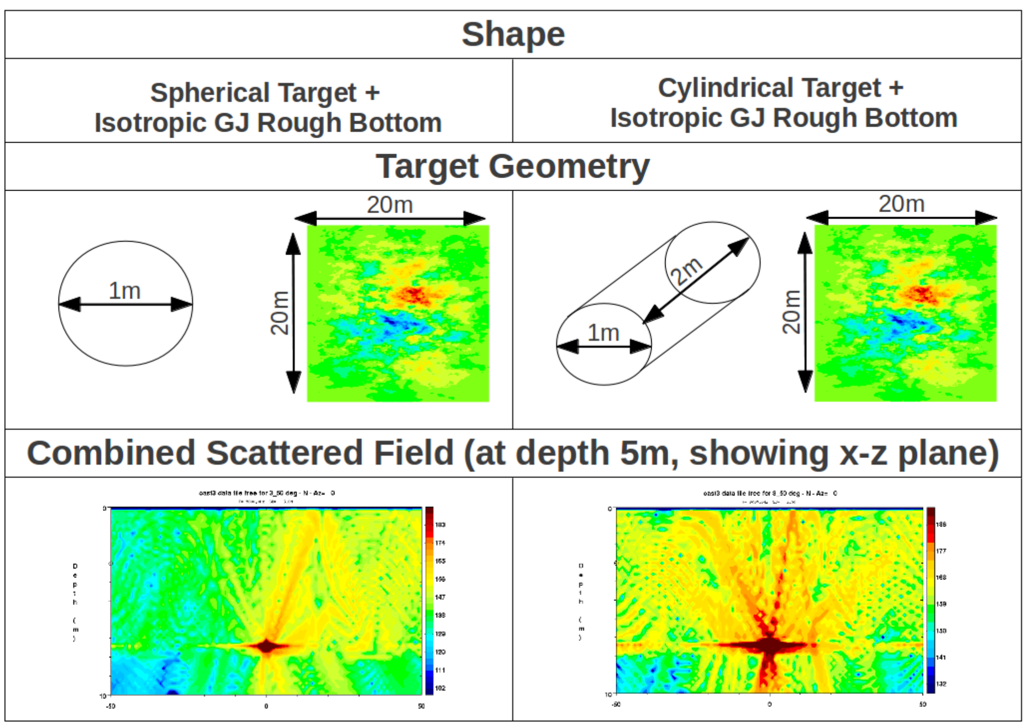

Figure 8. Comparison of scattered fields for spherical verses cylindrical targets in the presence of isotropic bottom roughness.

The result of this base case is perfect classification of all test examples, as shown in Fig. 9.

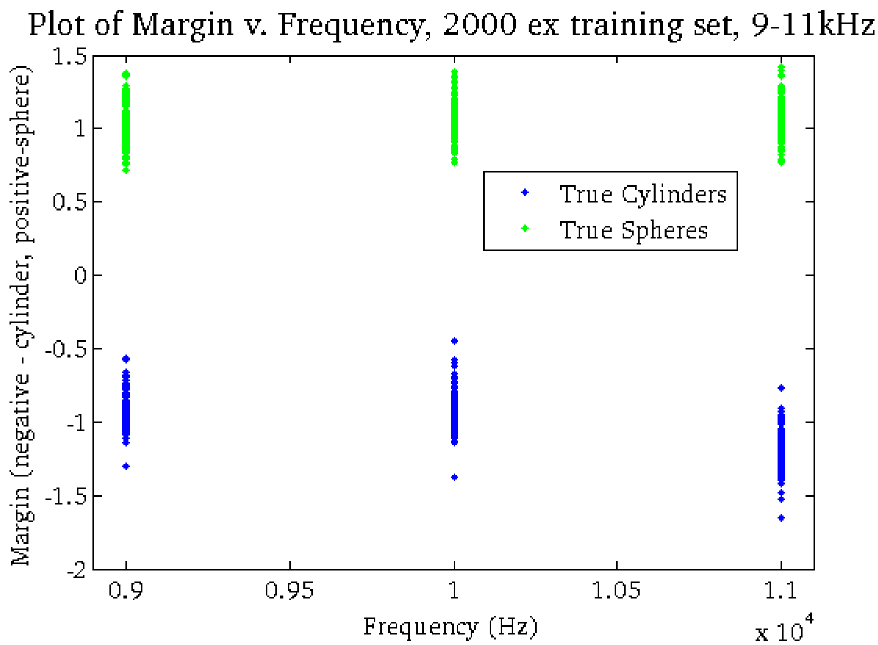

Figure 9. Classification results for 'clean' model classifying 'clean' test set.

Over a wider range of frequencies, the model does not do as well, as illustrated in Fig. 10:. Because the scattering pattern varies with frequency, the extreme values becomes less similar as the source becomes broader band. This suggests that if a broadband source is used multiple classification models may need to be used.

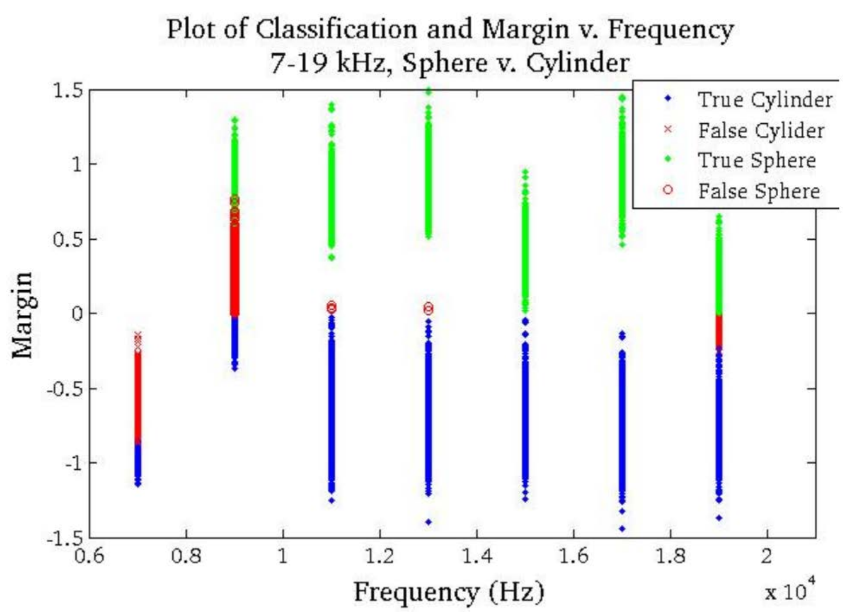

Figure 10. Model performance over a wider range of frequencies.

To show robustness to target and vehicle position estimation error, the values at each features in the test vector were mapped to some point at a distance $\Delta x, \Delta y, \Delta z$ from the original point. The original feature number is retained, and the new value applied, as though the vehicle thought it was at x,y,z but was sampling at $x+\Delta x, y+\Delta y, z+\Delta z$. The change in x,y, and z values were selected using a gaussian with a mean of zero and a standard deviation that varied. With a standard deviation of up to 20m, the 'clean' model was able to very successfully classify the shifted test set with sufficient confidence, with verification accuracy of about 90%.

To show robustness to environmental change, a model was trained using a fluid sand bottom, then used to classify training sets with elastic sand and limestone bottoms. The elastic sand test set had classification results as good as the fluid sand test set. The extreme case of the limestone bottom resulted in far more misclassification, but still showed some success in classification of targets.
In addition, this methodology was applied to regression for estimation of various environmental and target parameters. The greatest success was seen in the estimation of bottom anisotropy direction using amplitudes from the resultant scattered fields, shown in Fig. 11. The angle being estimated is the angle between the source and the bottom ridging, such that for the zero degree case the ridges are aligned with the source and in the ninety degree case the ridges are perpendicular to the source. Scattered fields were simulated using the SCATT Goff-Jordan anisotropic power spectrum bottom roughness model.

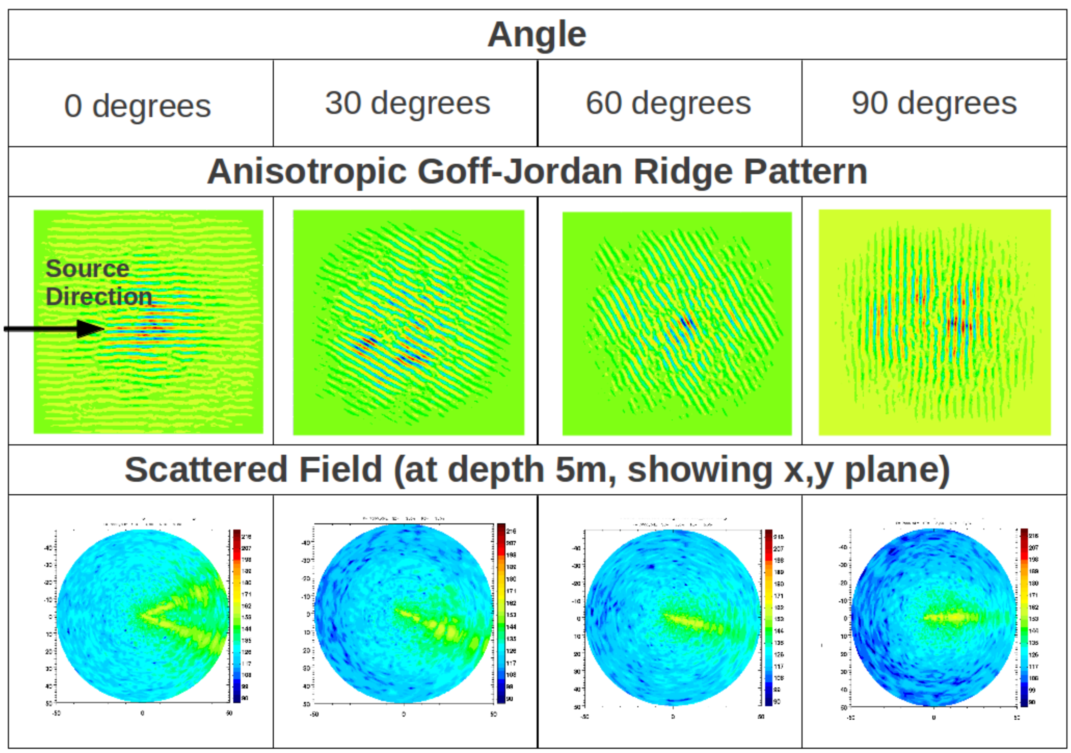

Figure 11. Comparison of bottom ripples and scattering patterns for different anisotropy angles.

An SVM regression model for ripple direction was trained using angle steps of 15 degrees. Bottom ridging direction angles for an independent test set were then estimated using that model. Several vehicle paths gave bottom direction estimation errors of less than 5 degrees at all angles of interest.

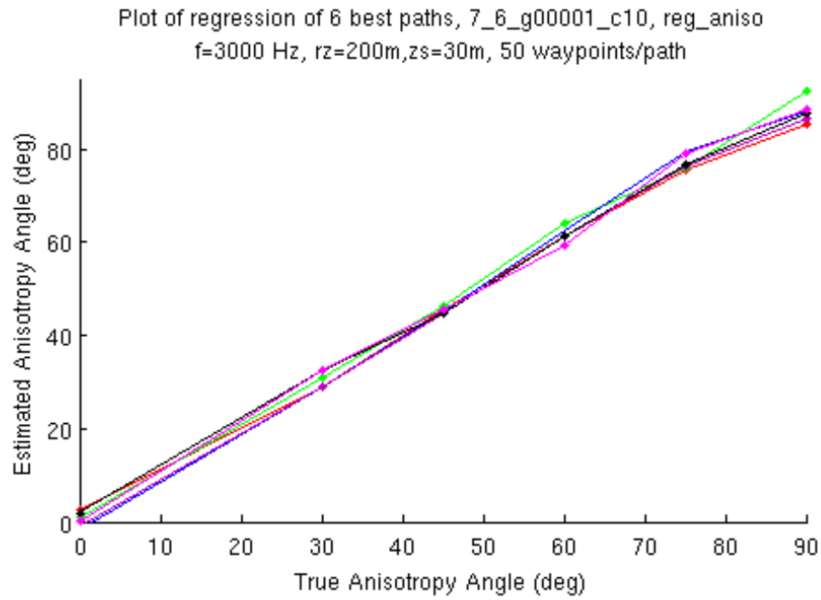

Figure 12. Anisotropy Angle Estimation verses True Anisotropy Angle for 5 best paths.

Autonomous Adaptive Oceanographic Feature Detection and Tracking with AUVs
Results from testing the newly developed autonomous and adaptive front tracking behavior, *BHV_FrontTrack*, using simulated AUVs in the MSEAS 4D dynamic ocean model of the Mid-Atlantic Bight region are described below. These include results from initial testing in a simplified static 'snapshot' of the MSEAS model, as well as results from ongoing test runs in the full 4D dynamic MSEAS model.

A. Static front tracking results
In simulation, a single AUV autonomously and adaptively tracked the shelf break front boundary (using the zig-zag front tracking behavior) in a *static* MSEAS Mid-Atlantic Bight model environment for more than 55 km over the duration of the simulation (26.4 hours). This is shown in Fig. 13. The distance along the front that the AUV could travel in this mode was only limited by the duration of the simulation runs. Although there were a few areas in which the AUV temporarily lost the front edge (often where the font curved sharply), the AUV was usually able to re-find the front edge autonomously and get back on course tracking the front.

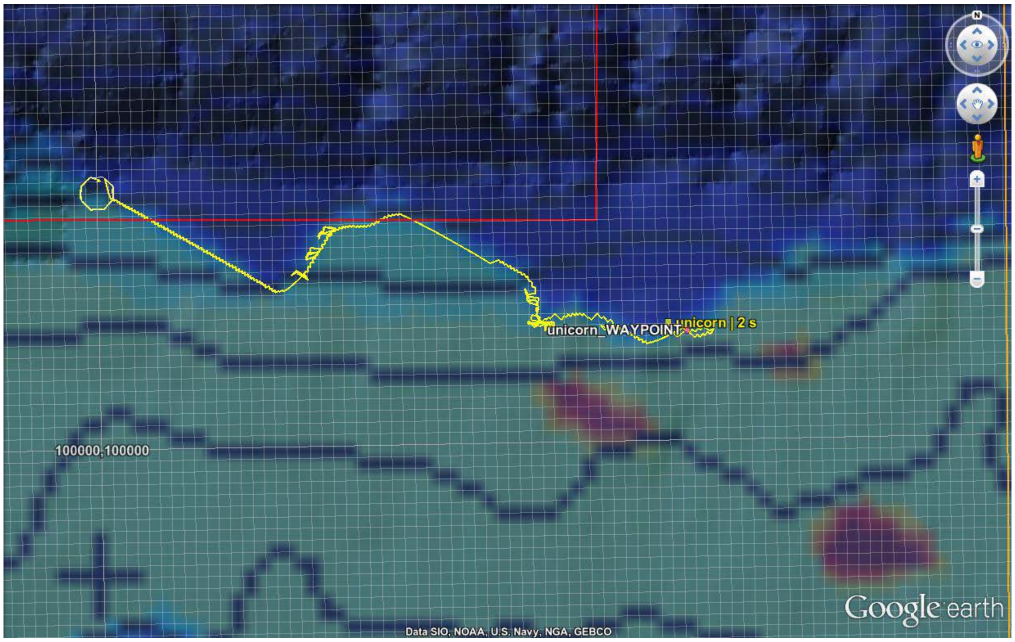

Figure 13. The Unicorn AUV (yellow track) tracking a static temperature front between 18°C (blue-shaded region) and 19°C (green-shaded region) along the Mid-Atlantic Bight shelf break front in a modified MSEAS ocean model. Unicorn tracked the front southeast over 55 km (as the crow flies) over the duration of the simulation (26.4 hours).

B. Dynamic front tracking results

Tracking a dynamic front is a much more challenging problem in that, on coastal ocean scales, the edge of a front can shift position by kilometers over the course of a few hours, making it difficult for an AUV swimming at about 2 m/s to detect and track the front boundary as it moves without getting left behind. In simulation, a single AUV autonomously and adaptively tracked the shelf break front boundary (using the zig-zag front tracking behavior) in a *dynamic* MSEAS Mid-Atlantic Bight model environment for more than 70 km over the duration of the simulation (39.9 hours). In contrast, a second AUV operating in the same environment at the same time only covered about 10-25 km over the same amount of time. This is shown in Fig. 14. Again, the distance along the front that the AUVs could travel in this mode was only limited by the duration of the simulation runs. Testing in the dynamic ocean environment is still ongoing to improve the robustness of the front tracking behavior.

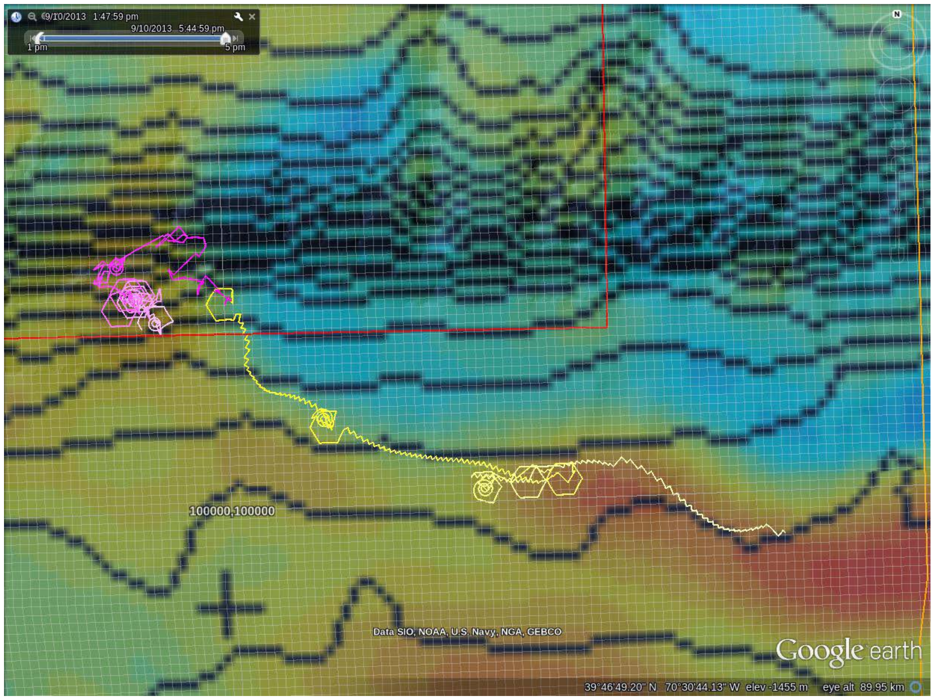

Figure 14. The Unicorn AUV (yellow track) and Macrura AUV (magenta track) tracking a dynamic temperature front between 15°C (light blue-shaded region) and 22°C (orange-shaded region) along the Mid-Atlantic Bight shelf break front in a 4D MSEAS ocean model. Unicorn tracked the front southeast over 70 km (as the crow flies) over the duration of the simulation (39.9 hours). Macrura tracked the front northwest over only 10 km (as the crow flies) over the same simulation duration.

Matched-Beam Differencing: Depth-tracking of a near surface source from a deep VLA

In the following simulation, the dictionary with varying source depths was created using OASES while the "actual" target signal was created using BELLHOP (ray tracing). In this simulated experiment the source has a bandwidth 100-200Hz with an initial range of 20 km and passing the array at 7 km CPA. The same trajectory was run for multiple depths ranging from about 5-200m. Three frequencies were used in order to determine the correct depth of the target. The results of each frequency were then weighted inversely proportional to lambda-weighted sample mean. Figures 15 shows the estimates, compared to the ground truth.

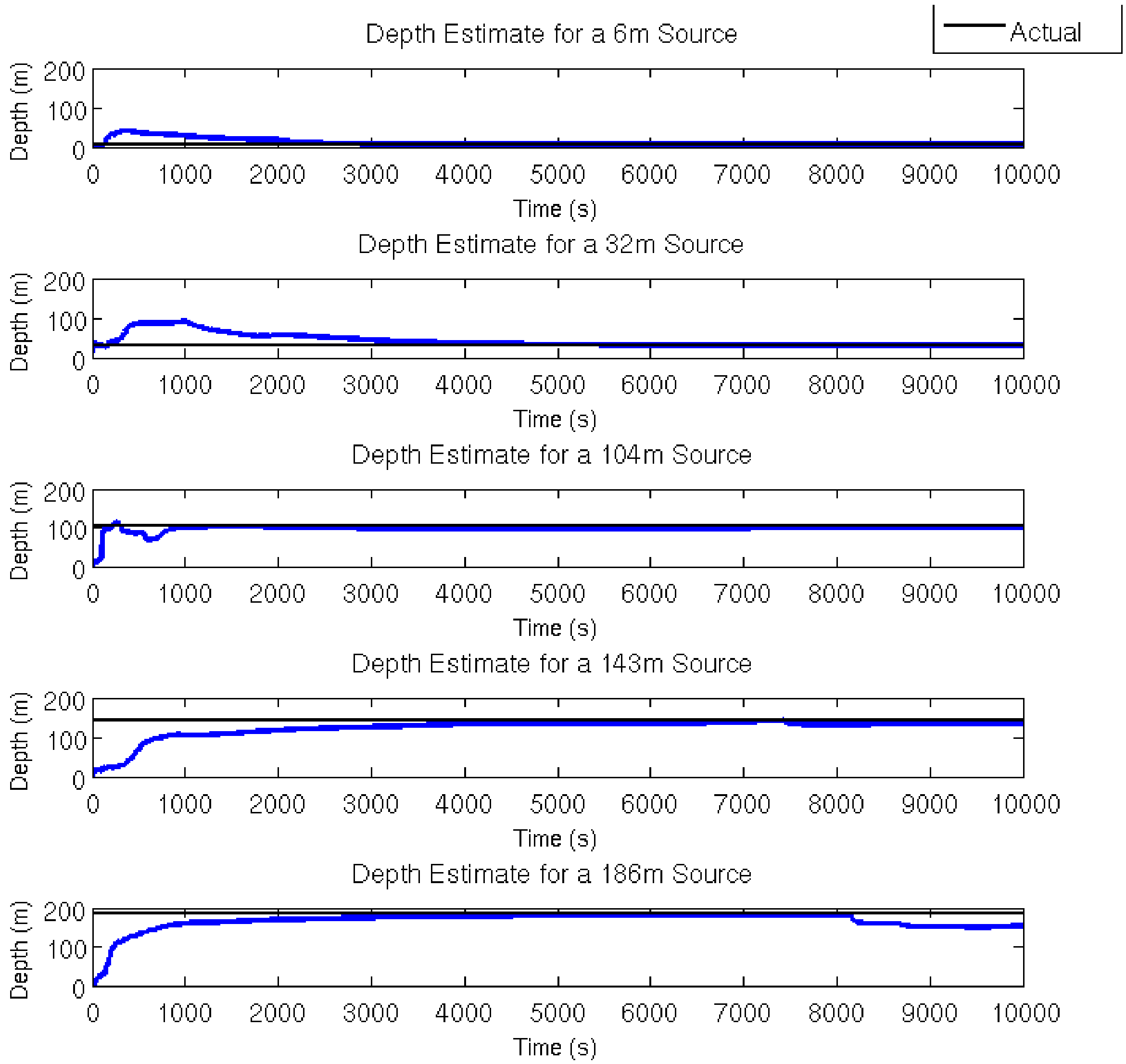

Figure 15 - Depth Estimates vs. Time for different source depths

Spatial Properties of the acoustic field in the near-surface deep ocean convergence zone

Convergence zones are well established as the key feature of propagation in the deep ocean from a near-surface source, creating increased intensity at a range of ~60 km. They are caused by upward refracting, deep sea isothermal gradient. Although much research has been done to determine the approximate location, skip distance and width of these convergence zones, not much as been done to determine how quickly the CZ onsets or other spatial properties. In the past year, it has been determined that a relationship exists between how quickly the CZ onsets, or the spatial "slope" representing the rate of the intensity in range, of the CZ vs source depth, sound speed profile and frequency, and a significant sensitivity is observed. As an example Fig. 17 shows the range derivative of the acoustic pressure at the onset of the CZ for a receiver at 60 m depth, for the profiles shown in Fig. 16.

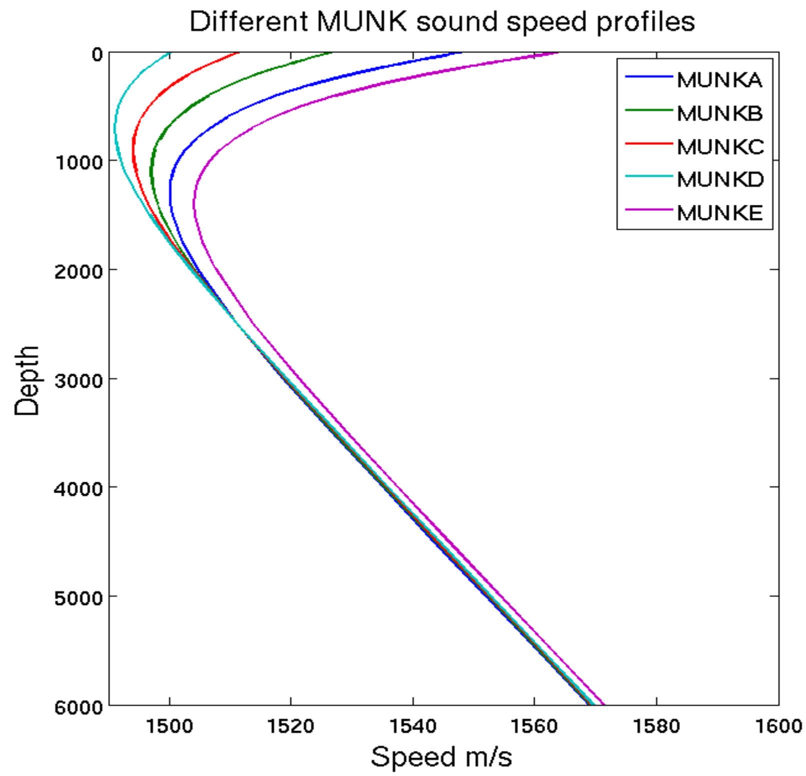

Figure 16 – Munk sound speed profiles investigated

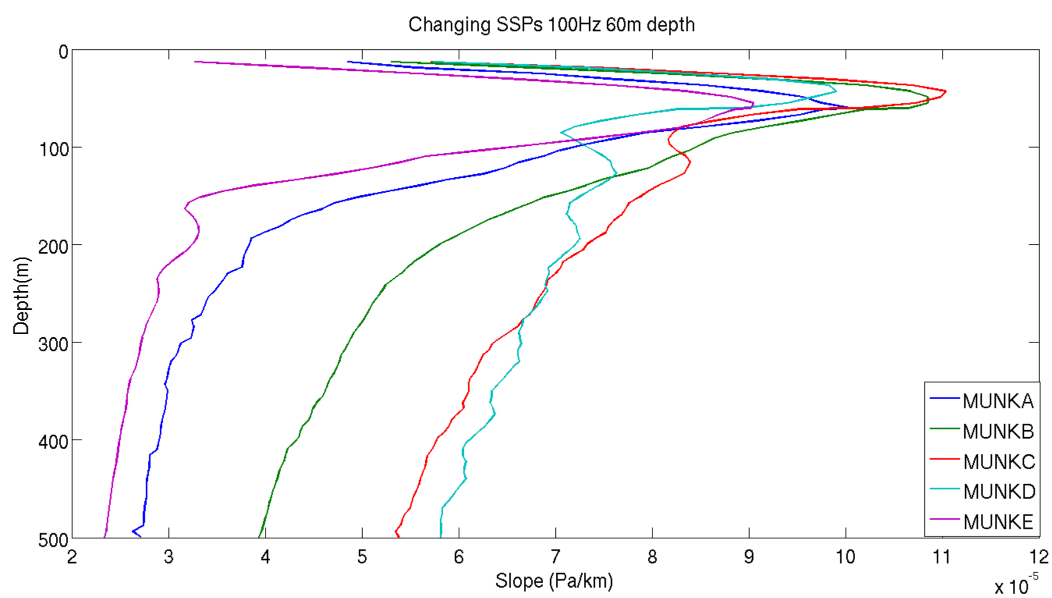

Figure 17 – Spatial Slope of CZ for 100Hz source at 60m depth for the sound speed profiles shown in Fig. 7

Autonomous Network Communicatioon and Control

Goby: Highly compressed encoding of vehicle positions

The technique for sending AUV "ownship" position estimates to a topside operator or collaborating vehicle was augmented in 2013 by the addition of a Kalman filter tracker (in addition to a last-heading tracker) (Schneider & Schmidt, A State Observation Technique for Highly Compressed Source Coding of Autonomous Underwater Vehicle Position, in press). It was demonstrated on two experimental data sets (GLINT10 and AGAVE07) and implemented in the field during the MBAT12 experiment (see Figure 18), leading to mean compression ratios as high as 93% (relative to a standard 32-bit integer representation) for the Cartesian position of the AUV. The position of the vehicle is needed to give operators assurance that the vehicle is performing properly and to correlate data measured with the physical location it was taken. However, historically, the position data took nearly all the acoustic throughput available, leaving little room for sending other data. This technique greatly reduces the overhead used by position telemetry, leaving room for more useful data such as contact and track reports.

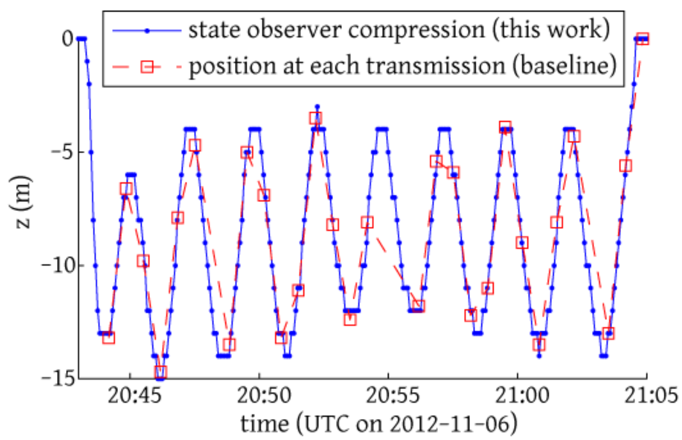

Figure 18: Reported depth of the AUV Unicorn during the MBAT12 Experiment using the standard technique (red) and the new state observer compression (blue). The new technique provides a low overhead method of "backfilling" vehicle positions for the operator to see an accurate trajectory.

RELATED PROJECTS

This effort has constituted part of the US component of the GOATS`2000 Joint Research Project (JRP) with the NATO Undersea Research Centre, and is currently collaborating with NURC under the Autonomous Sensing Networks Joint Research Projects (JRP).

The GOATS program developed out of the ONR Autonomous Ocean Sampling Network (AOSN) initiative completed in FY00, and is directly related to the Shallow Water Autonomous Mine Sensing Initiative (SWAMSI), initiated in FY04, and ending in FY12.

The Nested Autonomy architecture and acoustic modeling capabilities developed under GOATS has been applied in several other related programs MIT was partnering in, including the now completed AREA (Adaptive Rapid Environmental Assessment) component of the now completed ONR "Capturing Uncertainty" DRI, aimed at mitigating the effect of sonar performance uncertainty associated with environmental uncertainty by adaptively deploying environmental assessment resources.

The continued development and maintenance of the MOOS-IvP autonomy software being funded by ONR Code 31 (D. Wagner and B. Kamger-Parsi, Program Managers), and is also supported by funding from non-Government Institutions such as the Battelle memorial Institute.

The OASES modeling framework, which is being maintained, upgraded, and distributed to the community under this award, has been used intensively in all the related programs MIT is participating in.

TRANSITIONS

The environmentally and tactically adaptive autonomy software infrastructure using MOOS-IvP, developed under GOATS continues to be transitioned to other DoD programs. Thus, the depth-adaptive MFA sonar and platform control in the SHARK surveillance concept developed by DARPA under the Deep Sea Operations Program (PM Andy Coon) has been developed by MIT and is currently being integrated into the two 6000 m rated active sonar AUVs. The MOOS-IvP Platform Autonomy uses an embedded version of the GRAM environmental acoustic modeling infrastructure to dynamically relocate the platform for optimal sonar operation. The first deep sea demonstration is scheduled for Nov. 1013. This program also makes extensive use of the GOATS autonomous network sensing simulator, integrating MOOS-IvP with high-fidelity acoustic modeling, providing real-time simulation and processing chain stimulation.

Another 2013 transition is the adoption of the MOOS-IvP autonomy software infrastructure for the NRL reliant vehicle used in Brian Houston's LFBB program, as well as for other acoustic sensing platforms operated in the new NRL Autonomy facility. As part of this transition, PI Schmidt together with Dr. Mike Benjamin gave a 3-day short couse on MOOS-IvP autonomy to NRL scientists and engineers.

Also, NATO CMRE continues to be a very active user of the MOOS-IvP adaptive autonomy infrastructure and the associated environmental acoustic modeling infrastructure. All or most of their AUVs and ASCs are being operated using MOOS-ivP, and CMRE have developed a wide suite of dedicated autonomy processes and behaviors which have been successfully used in several field experiments in their Multistatic Active Acoustics program, and whenever possible they have fed their software mules back to the MOOS-IvP community for general use..

The Goby2 acoustic networking suite developed under GOATS and SWAMSI was initially officially released in Februrary, 2013. Goby2 has transitioned substantially inside and outside of the marine community. A few examples include:

- Bluefin Robotics has chosen the Goby2 marshalling language, DCCL, as its standard for underwater telemetry. DCCL will be spun-off as a standalone project in the next version to fast-track development and adoption as a standard with the marine community.
- The MIT DARPA Robotics Challenge Team (http://drc.mit.edu/) has adopted Goby2 for all the slow-link communications between the operator and disaster-relief humanoid robot. The MIT team placed 3rd overall in the June 2013 virtual challenge, and 2nd in network usage (i.e. 2nd fewest bytes used from the operator to the robot).
- The DARPA Deep Sea Operations (DSOP) team lead by Applied Physical Sciences is using Goby2 for all slow-link networking, including acoustic telemetry from autonomous underwater vehicles and Iridium satellite communications between remote surface nodes.

PUBLICATIONS

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2. S. Petillo and H. Schmidt. "Exploiting Adaptive and Collaborative AUV Autonomy for Detection and Characterization of Internal Waves." IEEE Journal of Oceanic Engineering, 2013. doi: 10.1109/JOE.2013.2243251. Available online (09/27/13): <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6502750&isnumber=4554198>.
3. S. Petillo. "Autonomous and Adaptive Front Tracking using AUVs in an MSEAS Dynamic Ocean Model." Presentation for MOOS-DAWG'13, MIT Cambridge, MA, 30-31 July, 2013.
4. T. Schneider and H. Schmidt, "A State Observation Technique for Highly Compressed Source Coding of Autonomous Underwater Vehicle Position," *IEEE Journal of Oceanic Engineering,* vol. PP, in press.
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6. T. Schneider, "iFrontSeat: a new approach for writing extensible MOOS-IvP "frontseat"-"backseat" payload interface drivers", MIT Technical Report, 2013.
7. T. Schneider, PhD Thesis, 2013
8. S. Danesh, MS Thesis, 2013
9. H. Schmidt, M.R. Benjamin, S. Petillo, T. Schneider, and R. Lum. "Nested Autonomy: Robust Operational Paradigm for Distributed Ocean Sensing." In Autonomous Marine Sensing Networks, T.B. Curtin, Ed., Springer, New York. In press.